Further study of double charmonium production in e^+e^- annihilation at Belle

P. Pakhlov[1]

[1]*ITEP, B.Cheremushkinskaya, 25, Moscow, Russia*
E-mail: pakhlov@itep.ru
(For the Belle Collaboration)

We report a new analysis of double charmonium production in e^+e^- annihilation using a data sample collected by the Belle experiment. We confirm our previous observation of the processes $e^+e^- \to J/\psi\eta_c(\chi_{c0}, \eta_c(2S))$ and perform an angular analysis for these processes. Processes of the type $e^+e^- \to \psi(2S)(c\bar{c})_{res}$ are observed for the first time. We also observe a new charmonium state – $X(3940)$, produced in the process $e^+e^- \to J/\psi X(3940)$.

PACS numbers: 13.66.Bc,12.38.Bx,14.40.Gx

The surprisingly large rate for processes of the type $e^+e^- \to J/\psi\,\eta_c$ and $J/\psi\,(c\bar{c})_{\rm non-res}$ observed by Belle [1] remains unexplained. In the Belle analysis with a data sample of $45\,{\rm fb}^{-1}$, the presence of the process $e^+e^- \to J/\psi\,\eta_c$ was inferred from the η_c peak in the mass spectrum of the system recoiling against the reconstructed J/ψ in inclusive $e^+e^- \to J/\psi\,X$ events. Following the publication of this result, the cross-section for $e^+e^- \to J/\psi\,\eta_c$ via e^+e^- annihilation into a single virtual photon was calculated to be $\sim 2\,{\rm fb}$ [2], which is at least an order of magnitude smaller than the measured value. Several hypotheses have been suggested in order to resolve this discrepancy. In particular, the authors of Ref. [3] have proposed that processes proceeding via two virtual photons may be important. Other authors [4] suggest that the final states observed by Belle contain a charmonium state and a $M \sim 3\,{\rm GeV}/c^2$ glueball, which are predicted by lattice QCD. Possible glueball contributions to the χ_{c0} signal are also discussed in Ref. [5]. In this paper we report an extended analysis of the $e^+e^- \to J/\psi\,(c\bar{c})_{\rm res}$ process to check the above hypotheses and provide extra information that might be useful to resolve the puzzle. This study is performed using a data sample of $155\,{\rm fb}^{-1}$ collected around the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric energy e^+e^- storage rings.

The analysis procedure is described in detail in Refs. [1, 6]. The recoil mass $M_{\rm recoil}$ is defined as $\sqrt{(E_{\rm CM} - E^*_{J/\psi})^2 - p^{*\,2}_{J/\psi}}$, where $E^*_{J/\psi}$ and $p^*_{J/\psi}$ are the J/ψ center-of-mass (CM) energy and momentum, respectively. The $M_{\rm recoil}(J/\psi)$ spectrum for the data is presented in Fig. 1: clear peaks around the nominal η_c and χ_{c0} masses are evident; another significant peak around $\sim 3.63\,{\rm GeV}/c^2$ is identified as the $\eta_c(2S)$. The authors of Ref. [3] estimated that the two-photon-mediated process $e^+e^- \to J/\psi\,J/\psi$ has a significant cross-section. To allow for a possible contribution from the exchange of two virtual photons, we fit the spectrum in Fig. 1 including all of the known narrow charmonium states below $D\overline{D}$ threshold. The fit results are listed in Table I. The yields for η_c, χ_{c0}, and $\eta_c(2S)$ have statistical significances between 3.8 and 10.7. The fit returns negative yields for the J/ψ and $\psi(2S)$; the χ_{c1} and χ_{c2} yields are found to be consistent with zero. A fit with all these contributions fixed at zero is shown as a solid line in Fig. 1; the dashed line in the figure corresponds to the case where the contributions of the J/ψ, χ_{c1}, χ_{c2} and $\psi(2S)$ are set at their 90% confidence level (CL) upper limit values; the dotted line is the background function.

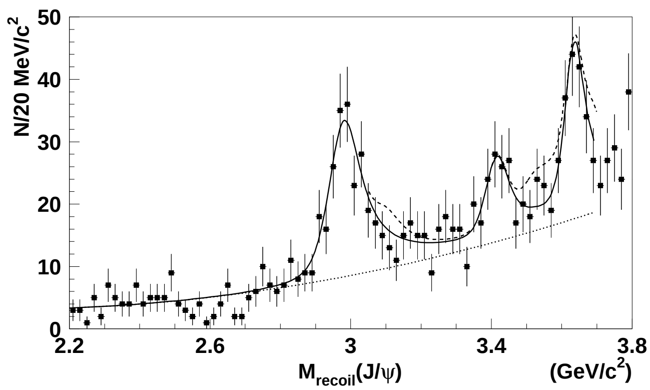

FIG. 1: The mass of the system recoiling against the reconstructed J/ψ. The curves are described in the text.

TABLE I: Summary of the signal yields (N), charmonium masses (M) and significances (σ).

$(c\bar{c})_{\rm res}$	N	M [GeV/c^2]	σ
η_c	235 ± 26	2.972 ± 0.007	10.7
J/ψ	-14 ± 20	fixed	—
χ_{c0}	89 ± 24	3.407 ± 0.011	3.8
$\chi_{c1}+\chi_{c2}$	10 ± 27	fixed	—
$\eta_c(2S)$	164 ± 30	3.630 ± 0.008	6.0
$\psi(2S)$	-26 ± 29	fixed	—

Given the arguments in Ref. [3], it is important to check for any momentum scale bias that may shift the recoil mass values and confuse the interpretation of peaks in the $M_{\rm recoil}$ spectrum. We use $e^+e^- \to \psi(2S)\gamma$,

TABLE II: The α parameters obtained from fits to the production and helicity angle distributions for $e^+e^- \rightarrow J/\psi\,(c\bar{c})_{\rm res}$.

	Separate		Simultan.
$(c\bar{c})_{\rm res}$	$\alpha_{\rm prod}$	$\alpha_{\rm hel}$	$\alpha_{\rm hel} \equiv \alpha_{\rm prod}$
η_c	$1.4^{+1.1}_{-0.8}$	$0.5^{+0.7}_{-0.5}$	$0.93^{+0.57}_{-0.47}$
χ_{c0}	$-1.7^{+0.5}_{-0.5}$	$-0.7^{+0.7}_{-0.5}$	$-1.01^{+0.38}_{-0.33}$
$\eta_c(2S)$	$1.9^{+2.0}_{-1.2}$	$0.3^{+1.0}_{-0.7}$	$0.87^{+0.86}_{-0.63}$

$\psi(2S) \rightarrow J/\psi\,\pi^+\pi^-$ events to calibrate and verify the recoil mass scale. From the study of the spectrum of recoil masses squared against $\psi(2S)$ in the data, we calculate that the J/ψ recoil mass is shifted by not more than $3\,{\rm MeV}/c^2$. As an additional cross-check we fully reconstruct double charmonium events. We find 3 pure events with $J/\psi\,\eta_c$ combinations with energies consistent with total CM energy. Based on the η_c yield in the $M_{\rm recoil}(J/\psi)$ distribution, we expect 2.6 ± 0.8 fully reconstructed events, consistent with the observed signal. Thus we conclude that the peak in $M_{\rm recoil}(J/\psi)$ is dominated by $J/\psi\,\eta_c$ production. We also search for fully reconstructed events with $J/\psi\,J/\psi$ combinations and find no such candidates in our data. Based on the calibration of the $M_{\rm recoil}(J/\psi)$ scale, the result of the fit to the $M_{\rm recoil}(J/\psi)$ distribution and the full reconstruction cross-check, we confirm our published observation of the process $e^+e^- \rightarrow J/\psi\,\eta_c$ and rule out the suggestion of Ref. [3] that a significant fraction of the inferred $J/\psi\,\eta_c$ signal might be due to $J/\psi\,J/\psi$ events.

The reconstruction efficiencies for the $J/\psi\,\eta_c$, $J/\psi\,\chi_{c0}$, and $J/\psi\,\eta(2S)$ final states strongly depend on $\theta_{\rm prod}$, the production angle of the J/ψ in the CM frame with respect to the beam axis, and the helicity angle $\theta_{\rm hel}$. We therefore perform an angular analysis for these modes before computing cross-sections. We fit the $M_{\rm recoil}(J/\psi)$ distributions in bins of $|\cos(\theta_{\rm prod})|$ and $|\cos(\theta_{\rm hel})|$, and correct the yield for the reconstruction efficiencies determined bin-by-bin from the MC. The results are plotted in Fig. 2, together with fits to functions $A(1+\alpha\cos^2\theta)$ (solid lines). We also perform simultaneous fits to the production and helicity angle distributions for each of the $(c\bar{c})_{\rm res}$ states, assuming $J/\psi\,(c\bar{c})_{\rm res}$ production via a single virtual photon and angular momentum conservation, thus setting $\alpha_{\rm prod} \equiv \alpha_{\rm hel}$. The values of the parameter α are listed in Table II. The angular distributions for the $J/\psi\,\eta_c$ and $J/\psi\,\eta_c(2S)$ peaks are consistent with the expectations for production of these final states via a single virtual photon, $\alpha_{\rm prod} = \alpha_{\rm hel} = +1$ [2]. The prediction for a spin-0 glueball contribution ($e^+e^- \rightarrow J/\psi\,\mathcal{G}_0$) to the $J/\psi\,\eta_c$ peak, $\alpha_{\rm prod} = \alpha_{\rm hel} \simeq -0.87$ [4], is disfavored. The process $e^+e^- \rightarrow \gamma^* \rightarrow J/\psi\,\chi_{c0}$ can proceed via both S- and D-wave amplitudes, and predictions for the resulting angular distributions are therefore model dependent. Our results disfavor the NRQCD expectation $\alpha_{\rm prod} = \alpha_{\rm hel} \simeq 0.25$ [2, 5], and are more consistent with S-wave production, where $\alpha_{\rm prod} = \alpha_{\rm hel} = -1$.

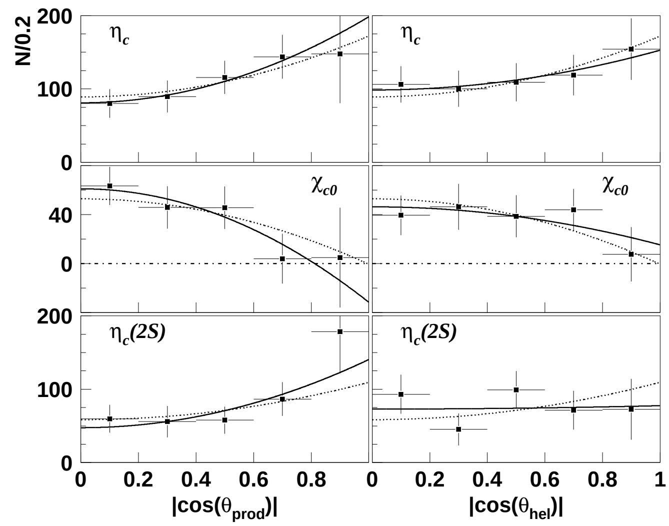

FIG. 2: Distributions of cosines of the production (left) and J/ψ helicity angles (right) for $e^+e^- \rightarrow J/\psi\,\eta_c$ (top row), $e^+e^- \rightarrow J/\psi\,\chi_{c0}$ (middle row) $e^+e^- \rightarrow J/\psi\,\eta(2S)$ (bottom row). The solid lines are results of the individual fits; the dotted lines are the simultaneous fit results.

To calculate the cross-sections we fix the production and helicity angle distributions in the MC to $1+\cos^2\theta$ for $J/\psi\,\eta_c(\eta_c(2S))$, and to $1-\cos^2\theta$ for $J/\psi\,\chi_{c0}$. To reduce the model dependence of our results due to the effect of initial state radiation, whose form-factor dependence on Q^2 of the virtual photon is unknown, we calculate cross-sections in the Born approximation. As in Ref. [1], we present our result in terms of the product of the cross-section and the branching fraction of the recoil charmonium state into more than 2 charged tracks: $\sigma \times \mathcal{B}_{>2}$, where $\mathcal{B}_{>2}((c\bar{c})_{\rm res}) \equiv \mathcal{B}((c\bar{c})_{\rm res} \rightarrow > 2\,{\rm charged})$. The cross-sections are given in Table IV.

We perform a similar study with reconstructed $\psi(2S) \rightarrow J/\psi\,\pi^+\pi^-$ decays to search for $e^+e^- \rightarrow \psi(2S)(c\bar{c})_{\rm res}$ processes. The recoil mass spectrum for the data is presented in Fig. 3: peaks corresponding to the η_c, χ_{c0}, and $\eta_c(2S)$ can be seen. The fit to the $M_{\rm recoil}(\psi(2S))$ distribution is identical to the $M_{\rm recoil}(J/\psi)$ fit, but due to the limited sample in this case, the masses of the established charmonium states are fixed to their nominal values; the $\eta_c(2S)$ mass is fixed to $3.630\,{\rm GeV}/c^2$ as found from the $M_{\rm recoil}(J/\psi)$ fit. The signal yields are listed in Table III. Significances for the individual η_c, χ_{c0}, and $\eta_c(2S)$ peaks are in the range $3 \sim 4\sigma$; the significance for $e^+e^- \rightarrow \psi(2S)\,(c\bar{c})_{\rm res}$, where $(c\bar{c})_{\rm res}$ is a sum over η_c, χ_{c0}, and $\eta_c(2S)$, is estimated to be $5.3\,\sigma$. In Fig. 3 the result of a fit with only η_c, χ_{c0} and $\eta_c(2S)$ contributions included is shown as a solid line; the dashed line shows the case where the J/ψ, χ_{c1}, χ_{c2},

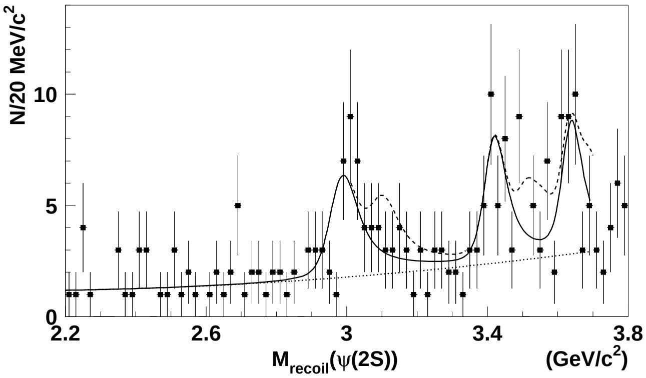

FIG. 3: The mass of the system recoiling against the reconstructed $\psi(2S)$. The curves are described in the text.

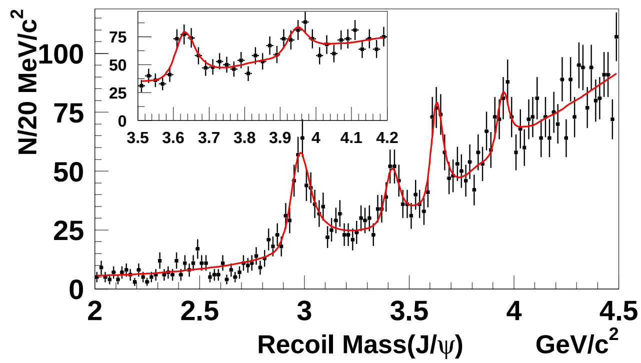

FIG. 4: The mass of the system recoiling against the reconstructed J/ψ. The curves are described in the text.

TABLE III: Summary of the signal yields (N) and significances (σ).

$(c\bar{c})_{\rm res}$	N	σ
η_c	36.7 ± 10.4	4.2
J/ψ	6.9 ± 8.9	—
χ_{c0}	35.4 ± 10.7	3.5
$\chi_{c1}+\chi_{c2}$	6.6 ± 8.0	—
$\eta_c(2S)$	36.0 ± 11.4	3.4
$\psi(2S)$	-8.3 ± 8.5	—

and $\psi(2S)$ contributions are set at their 90% CL upper limit values; the dotted line is the background function. Finally, the calculated products of the Born cross-section and the branching fraction of the recoiling charmonium state into two or more charged tracks ($\sigma \times \mathcal{B}_{>0}$, where $\mathcal{B}_{>0}((c\bar{c})_{\rm res}) \equiv \mathcal{B}((c\bar{c})_{\rm res} \rightarrow > 0\,{\rm charged}))$ are presented in Table IV.

Using even larger data set of $280\,{\rm fb}^{-1}$, which became available by the summer 2004, we extend the analysis of the recoil masses against J/ψ above $D\overline{D}$ threshold. We find another significant peak around the mass of $M \sim 3.940\,{\rm GeV}/c^2$ (Fig. 4). We denote this peak as $X(3940)$. The fit to this spectrum includes the signal function, which is a sum over four charmonium states: η_c, χ_{c0}, $\eta_c(2S)$, $X(3940)$, and the background function that includes also the possible contribution from $e^+e^- \to J/\psi D\overline{D}$ events. The mass of the new charmonium state found by the fit is $M_X = (3.940 \pm 0.012)\,{\rm GeV}/c^2$; the signal yield is $N = 149 \pm 33$ events and the significance of the signal is $4.5\,\sigma$. The intrinsic width of the state is consistent with zero within a large error due to poor $M_{\rm recoil}$ resolution. We set an upper limit on Γ to be $96\,{\rm MeV}/c^2$ at 90% CL.

TABLE IV: Summary of the cross-sections for $e^+e^- \to J/\psi\,(c\bar{c})_{\rm res}$ and $e^+e^- \to \psi(2S)\,(c\bar{c})_{\rm res}$. $\mathcal{B}_{>2(>0)}$ denotes the branching fraction for final states containing more than 2 (at least one) charged tracks. The units are fb, and the upper limits are set at 90% CL.

$(c\bar{c})_{\rm res}$	$\sigma_{Born} \times \mathcal{B}_{>2}$	$\sigma_{Born} \times \mathcal{B}_{>0}$
η_c	$25.6 \pm 2.8 \pm 3.4$	$16.3 \pm 4.6 \pm 3.9$
J/ψ	< 9.1	< 16.9
χ_{c0}	$6.4 \pm 1.7 \pm 1.0$	$12.5 \pm 3.8 \pm 3.1$
$\chi_{c1}+\chi_{c2}$	< 5.3	< 8.6
$\eta_c(2S)$	$16.5 \pm 3.0 \pm 2.4$	$16.0 \pm 5.1 \pm 3.8$
$\psi(2S)$	< 13.3	< 5.2

We also search for the decay of $X(3940)$ into $D\overline{D}$ and $D\overline{D}^*$ final states by reconstructing one of D mesons and requiring the second $\overline{D}$ or $\overline{D}^*$ in the recoil mass spectrum against reconstructed $J/\psi D$ combinations. We find a significant signal of $e^+e^- \to J/\psi X(3940)$ process when the event is tagged as $X(3940) \to D\overline{D}^*$, while no signal is found for $X(3940) \to D\overline{D}$. We thus conclude that the dominant $X(3940)$ decay mode is $D\overline{D}^*$, and this state has a different nature from the recently found enhancement in $J/\psi\omega$ mass distribution around the same mass [7].

In summary, using a data set of $155\,{\rm fb}^{-1}$ we confirm our published observation of $e^+e^- \to J/\psi\,\eta_c$, $J/\psi\,\chi_{c0}$ and $J/\psi\,\eta_c(2S)$ and find no evidence for the process $e^+e^- \to J/\psi\,J/\psi$. We have calculated the cross-sections for $e^+e^- \to J/\psi\,\eta_c$, $J/\psi\,\chi_{c0}$, and $J/\psi\,\eta_c(2S)$ with better statistical accuracy and reduced systematic errors and set an upper limit for $\sigma(e^+e^- \to J/\psi\,J/\psi) \times \mathcal{B}(J/\psi \to > 2\ {\rm charged})$ of 9.1 fb at the 90% CL. Although this limit is not inconsistent with the prediction for the $J/\psi\,J/\psi$ rate given in Ref. [3], the suggestion that a large fraction of the inferred $J/\psi\,\eta_c$ signal consists of $J/\psi\,J/\psi$ events is ruled out. We have measured the production and helicity angle distributions for $e^+e^- \to J/\psi\,\eta_c$, $J/\psi\,\chi_{c0}$, and $J/\psi\,\eta_c(2S)$; the distributions are consistent with expectations for these states, and disfavor a spin-0 glueball contribution to the η_c peak. We observe $\psi(2S)(c\bar{c})_{\rm res}$

production for the first time, and find that the production rates for these final states are of the same magnitude as the corresponding rates for $J/\psi\,(c\bar{c})_{\rm res}$. Finally, using a larger data set we observe the new narrow charmonium state at the mass $M_X = (3.940 \pm 0.012)\,\mathrm{GeV}/c^2$.

[1] K. Abe *et al.* (Belle Collab.), Phys. Rev. Lett. **89**, 142001 (2002).
[2] E. Braaten and J. Lee, Phys. Rev. **D67**, 054007 (2003); predictions for the angular distributions are listed in the appendix.
[3] G.T. Bodwin, J. Lee and E. Braaten, Phys. Rev. Lett. **90**, 162001 (2003).
[4] S.J. Brodsky, A.S. Goldhaber and J. Lee, Phys. Rev. Lett. **91**, 112001 (2003).
[5] S. Dulat, K. Hagiwara and Z.H. Lin, arXiv:hep-ph/0402230
[6] K. Abe *et al.* (Belle Collab.), Phys. Rev. **D70**, 071102 (2004).
[7] K. Abe *et al.* (Belle Collab.), BELLE-CONF-0473, hep-ex/0408126.